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A 16.5 Giga Events/s 1024 × 8 SPAD Line Sensor with per-pixel Zoomable 50ps-6.4ns/bin Histogramming TDC

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Abstract

A 1024 × 8 single photon avalanche diode (SPAD) based line sensor for time resolved spectroscopy is implemented in 0.13 µm imaging CMOS with 23.78 µm pixel pitch at 49.31% fill factor. The line sensor can operate in single photon counting (SPC) mode (65 giga-events/s), time-correlated single photon counting (TCSPC) mode (194 million events/s) or histogramming mode (16.5 giga-events/s), increasing the count rate up to 85 times compared to TCSPC operation. This performance is enabled by a 512 channel histogramming TDC with 50ps-6.4ns/bin zoomable time resolution. **Keywords:** CMOS, SPAD, TCSPC, Histogramming, Time-resolved spectroscopy.

Introduction

CMOS SPAD technology enables massively parallelized counting and timing of single photons in imaging, line and single point sensor formats [1]. The per-pixel time-resolution or gating offered by SPAD line sensors opens up new applications in hyperspectral scanning systems in microscopy, endoscopy and aerial monitoring as well as new modalities in ring-down, fluorescence lifetime and Raman spectroscopies [2][3][4][5]. Several architectures have been explored from 4 gated counters [2], per-pixel time to digital converters (TDCs) [3], time-gated memories [4], in-pixel center-of-mass computation [5], and off-chip FPGA TDCs [6]. A bottleneck is implied by readout of per pixel time-events from TDCs to implement off-chip TCSPC locking the pixel dynamic range to the available I/O rate. We employ on-chip histogramming [7] for the first time at a per-pixel level achieving up to two orders of increase in the SPAD photon processing rates [1] enabling fast scanning or low I/O power time-resolved spectroscopic imaging.

Line Sensor Design

A photomicrograph of the line sensor is shown in Fig. 1. The die, measuring 12.648 × 1.990 mm, is fabricated in a 130nm CMOS imaging technology with 23.78 µm pixel pitch at 49.31% fill factor. A simplified block diagram of the sensor is shown in Fig. 2. The sensor has 2 SPAD line arrays, one optimized for 450nm to 550nm (blue SPADs), the other optimized for 600nm to 900nm (red SPADs). Each pixel has 16 blue and 16 red SPADs which can be accessed as 2 interleaved lines of 512 pixels × 11.89 µm wide to double the spectral resolution. The sensor has 512 × 16-bit, 50ps TDC blocks (Fig. 3). The TDCs [9] can operate in standard TCSPC mode using global pixel write and pixel reset control signals for transferring generated time-event values off-chip. The TDCs can also operate in histogramming mode (Fig. 4), passing time-event values to the respective histogramming block (Fig. 5), in which case write and reset control signals (TDC_WRITE and TDC_RESETn in Fig. 3) are generated on-chip and by each TDC independently. In histogramming mode, the first 12-bits of the 16-bit TDC are used, providing up to a 204.8 ns wide histogramming window. The histogram block has 32 bins and each bin is implemented as a 10-bit ripple counter. For increased dynamic range two consecutive bins can be chained, halving the histogram bins to 16 while doubling the bin width to 20-bit. Bin widths can also be configured from 1 to 128 time-events per bin under the control of the Histogram decoder (Fig. 5). Together with a 50 ps resolution on-chip delay generator, this feature allows positioning and zooming of the histogram window to the spectral peak. In SPC mode, the first 4 histogram bins are used in chain mode creating two independent time gated 20-bit counters (SPCA and SPCB) allowing rapid fluorescence lifetime estimation. Simultaneous readout and detection is supported to achieve 100% temporal aperture ratio. Optical throughputs of 65 giga-events/s in SPC mode, 194 million events/s in TCSPC mode and 16.5 giga-events/s in histogramming mode are achieved. Histogramming mode increases the count rate up to 85 times compared to TCSPC operation. Throughputs of 8.5 giga-events/s in a 256 × 1 line sensor [6] and 1.7 giga-events/s in a single point sensor [7] have previously been reported. SPADs can be individually enabled in each pixel to optimize sensor dark count rate (DCR). Time gating (TG) can be applied to all modes with variable gates set up by the on-chip delay generator. TG SPC mode can process multiple events during a single laser pulse with the pulse shortening OR-tree architecture [8]. Furthermore, the TG can be set to time-gate OFF or ON an event during the laser pulse period. The mean FWHM of the instrument response function (IRF) of the blue SPADs is 114ps with a 2V excess bias voltage (Fig. 6).

Experimental Results

The line sensor was tested under controlled LED illumination triggered at 100 MHz to measure the maximum count rate in all modes. As shown in Fig. 7, per-pixel histogramming achieves ~1/4 SPC count rate demonstrating our ability to maximize TCSPC event timing. In order to demonstrate the time-resolving spectral capabilities of the sensor we investigated Fluorescein-Rhodamine FRET. We placed the line sensor in a spectrograph and captured fluorescence from the sample illuminated by a 483 nm pulsed laser diode (20 MHz repetition rate). In Fig. 8 we present a time-resolved spectrum of the mixture obtained in TCSPC mode (Fig. 8(a)) and the on-chip histogramming mode (Fig. 8(b)). Two clear peaks are obtained at wavelengths of 527 nm and 584 nm, with two distinct lifetimes. The fluorescence lifetimes are as expected for the dyes involved (Fig. 9). Fig. 10 shows that the on-chip histogramming data acquisition rate per wavelength is up to 15 times greater than raw TCSPC mode. This increases to 68 times with a Fluorescein sample alone. Zooming from 3.2 ns/bin to 0.8 ns/bin is demonstrated in Fig. 11. The sensor empowers existing time-resolved spectroscopy and imaging applications and enables new ones.

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References

[1] Palubiak et al, IEEE STQE, 2014. [2] Pancheri et al, ESSCIRC 2009. [3] Nissinen et al, AICSP Springer, 2015. [4] Maruyama et al, IEEE SSC, 2014. [5] Krstajić et al, Opt. Ex. 2015. [6] Burri et al, Proc. SPIE, 2016. [7] Dutton et al, ISSCC 2015. [8] Braga et al, ISSCC 2013. [9] Richardson et al, IEEE CICC 2009.

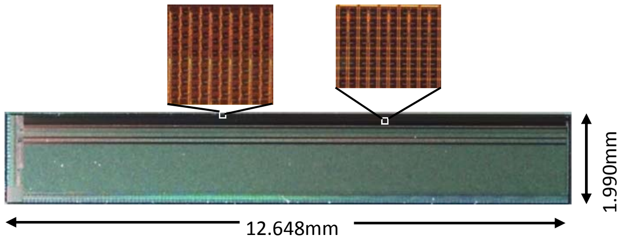


Fig. 1 Photomicrograph of the line sensor with inset showing blue and red SPADs of 5 pixels

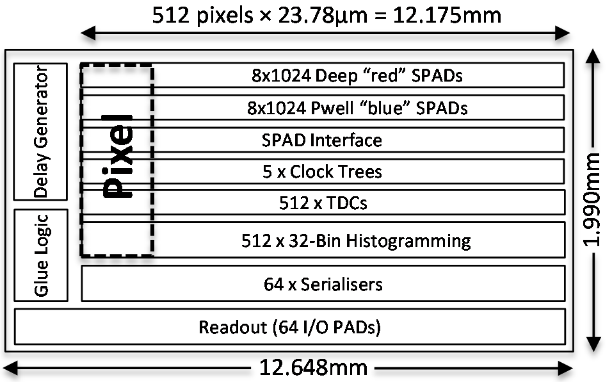


Fig. 2 Line sensor block diagram

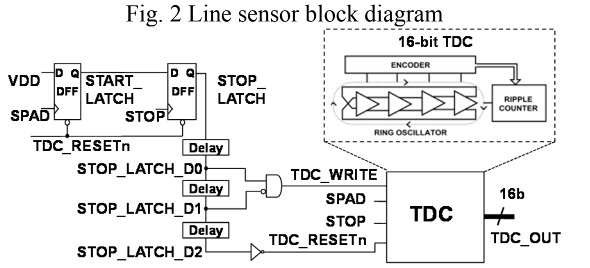


Fig 3 Edge triggered self-resetting TDC block

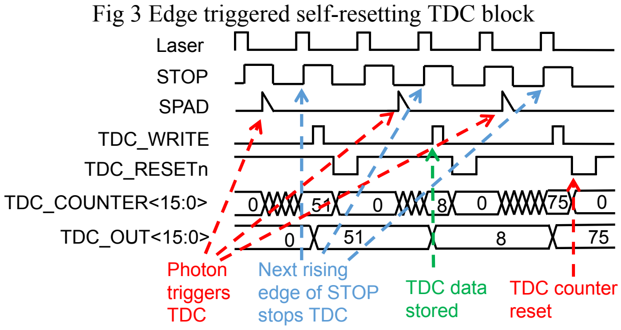


Fig. 4 TDC timing diagram in Histogram mode

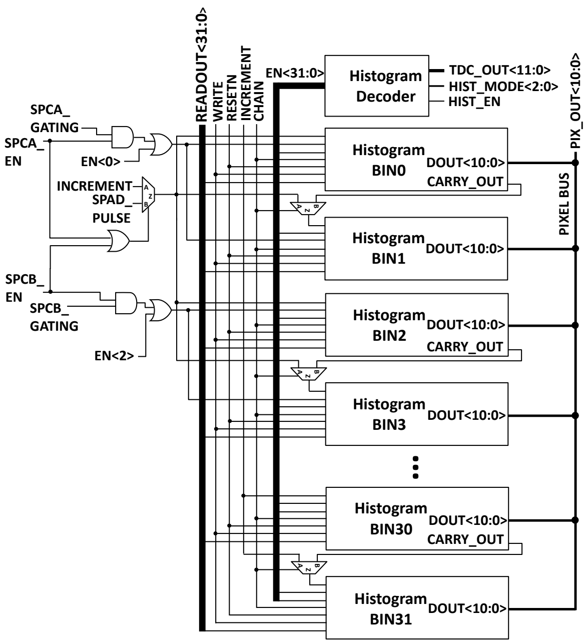


Fig 5 32-Bin Histogram block

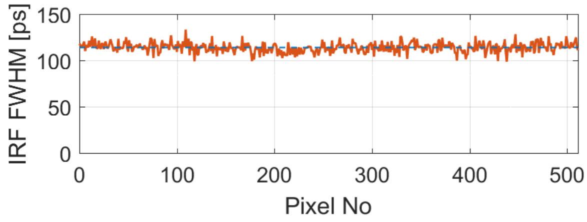


Fig. 6 IRFs of blue SPADs (Mean FWHM = 114ps)

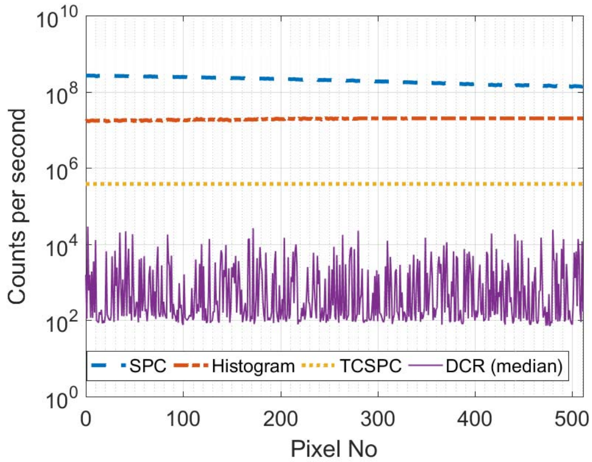
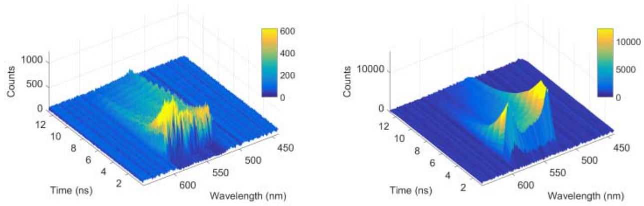
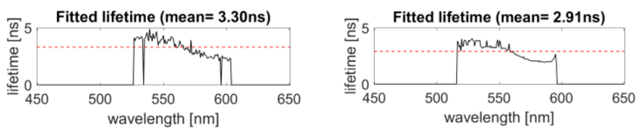


Fig. 7 Maximal count rate comparisons



(a) (b)

Fig. 8 Time resolved 3-D spectras based on (a) TCSPC and (b) Histogram modes



(a) (b)

Fig. 9 Estimated lifetimes based on (a) TCSPC and (b) Histogram modes

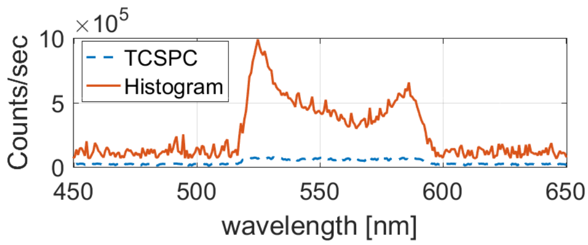
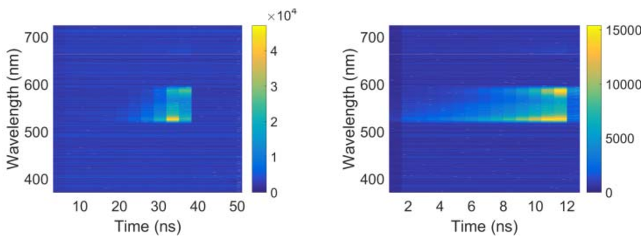


Fig. 10 Count rate comparison between TCSPC and Histogram modes



(a) 3.2ns/bin (b) 0.8ns/bin

Fig. 11 Zooming feature of Histogram mode